Multi-scale modeling for more affordable engineering of composite materials and structures

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Outline

- About e-Xstream engineering

- Digimat for the multi-scale nonlinear analysis of materials & structures

- Solutions for:
  - Design of short fiber reinforced plastic parts,
  - Computation of composite allowables,
  - Virtual testing of discontinuous fiber composites,
  - ICME of additive manufacturing parts.
e-Xstream, *The material modeling company*

- Software & Engineering 100% focused on material modeling.
- Founded in May 2003
- A team of 53 including 21 PhD and 26 MS Eng.
- HQ in Europe (Belgium/Luxembourg)
- 250+ major customers
- An MSC Software Company since September 2012
  - 50 years in Simulation/1000+ persons/20 countries
MSC corporate strategy
From Material Microstructure to End Product Performance

Speed-up the development of new material systems

Virtual Characterization of material coupons

Engineering of Composite Parts & Systems
Nonlinear Micro Mechanics – *MF & FE*

Input

- \( \sigma \)
- \( \varepsilon \)
- Matrix

- \( \varepsilon \)
- Filler

- \( a_r \)
- \( w \) [%]

Homogenization

- Localization
- Averaging

Output

Finite Element

Mean Field

\[ E \rightarrow \Sigma \]

\[ \Delta \varepsilon_r = \langle \Delta \varepsilon(x) \rangle_r = H_r : \Delta E \]

\[ \Delta \bar{\sigma} = \bar{c}(c_r) : \Delta \bar{\varepsilon} \]

\[ \varepsilon_r \]

\[ \Delta \sigma_r = c_r : \Delta \varepsilon_r \]

\[ \bar{\varepsilon} \]

Stress vs. Strain

- Experiment
- Scaling (70%)

Fiber orientation
Complete A – Z solution for RVE analysis with Digimat-FE

- **Mesh**
  - Tetrahedral / Voxel

- **RVE**
  - Geometry / BCs
  - Materials
  - Microstructure

- **Solution**
  - Iterative / Direct

- **Results**
  - Fields
  - Distributions
  - Effective Properties

- **External solvers**
  - Marc, Abaqus, Ansys, LS-Dyna
RVEs from Digimat-FE
Micro and Hybrid solution procedures

Constituent materials
- Fibres
- Matrix
- Microstructure
  - Orientation
  - Length
  - Fraction

Homogenization
- Digimat-MF
  - Mean-field
- Digimat-FE
  - Direct

Reduction
- Micro solution procedure (strong coupling between the scales)
- Hybrid solution procedure (weak coupling between the scales)
- Macroscopic

Processes (injection, draping, RTM, thermo-forming, ...)

Structural
- Digimat-CAE

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Link to process

- **Structural engineering**: Influence of process (via microstructure, residual stresses, ...) over structural performance.

**SFRP processing**
- Fiber orientation, temperature, residual stresses, weldlines, porosity, fiber length and volume fraction.
  - From Moldflow, Moldex3D, Sigmasoft, Simpoe, REM3D, Timon3D.

**CFRP processing**
- Fiber orientation (UD & 2D woven) and porosity.
  - From Simulayt, PAM-Form, Aniform, PAM-RTM.

**Metal casting**
- Porosity
  - From ProCast and Magmasoft.

**Measurements (CT scan)**
- Fiber orientation and volume fraction.
  - From VolumeGraphics
Connecting *tools* to provide *solutions*

**RP**
- Virtual design of reinforced plastics parts
  - Short & long fiber reinforced plastics
  - Injection molded parts
  - Continuum and shell meshes for process & structural simulations
  - Embedded fiber orientation estimator

**VA**
- Virtual allowables for CFRP
  - UD & 2D wovens
  - OHT, OHT, bearing, filled holed …
  - Modeling of variabilities
  - Statistical post-processing (A & B allowables)

**AM**
- Process simulation of additive manufacturing
  - Unreinforced and reinforced polymers
  - FFF & SLS processes
  - Warpage & residual stress computations
  - Export to structural CAE
Digimat-RP – Virtual design of SFRP parts
Aircraft Bracket: Carbon fiber reinforced thermoplastic for metal replacement

Workflow

1. T-Bracket assembled to metallic plates and loaded by a fast dynamic pull-out load

2. Map the local orientation tensor resulting from the injection process

3. Calibration of a elasto-plastic material behavior for the CF/PEEK

4. Run the coupled analysis accounting the local fiber orientation
Digimat-VA: Virtual Allowable computation

Materials

UD & 2D wovens

Layup

Test

Variability

Performance

Statistical Allowable

UNT/UNC

OHT/OHC

Filled holed

Bearing
Curing

- **Model allows to:**
  - Evolution of curing with temperature.
  - Model viscous effect during plateau (thermo-viscoelastic material model).
  - Stiffness increase due to material cure.
  - Shrinkage due to material cure.
  - Thermal effects due to high change of temperature.

![Equivalent von Mises Stress](image1)

![Temperature vs Time](image2)

![Stress vs Time](image3)
Progressive failure of CFRP

- 3D slice of unidirectional carbon-epoxy composite
- Transverse shear loading
- Elastic with damage constituents behavior
- Fiber-matrix debonding using cohesive elements

![Graph showing stress-strain relationship](graph.png)
Progressive failure of CFRP

Failure criterion

Damage leading to stiffness reduction

Zoom over fiber-matrix debonding (deformation scale factor of 5)
Material RVE

Typical RVE with 10% resin pockets in volume

Same RVE after hiding the elements in the resin pockets

Orientation tensor
e.g. statistical description of the fiber orientation at this scale

Progressive failure model for CFRP (UD) based on mean-field homogenization

Deterministic orientation description at this scale

\[
\left(\frac{\sigma_n}{S_n}\right)^2 + \left(\frac{\sigma_t}{S_t}\right)^2 > 1 \text{ if } \sigma_n \geq 0, \text{ otherwise } \left(\frac{\sigma_t}{S_t}\right)^2 > 1
\]
Calibration against the DCB test

High sensitivity with respect to $S_n$
Effective properties dispersion

Various realizations respecting the same statistical description leads to dispersion of effective properties
Process simulation – Digimat-AM

• Additive manufacturing processes:
  – SLS
  – FFF

• Materials:
  – Filled & unfilled polymers

• Predictions:
  – Warpage & residuals stresses.
  – Micro/meso structure
Process simulation – Digimat-AM
Material engineering
Structural engineering AM components
Holistic Material Modeling Strategy

- **Materials**
  - Chopped & Continuous Fibers
  - (Nano) Fillers

- **Physics**
  - (Thermo)-Mechanical
  - Thermal
  - Electric

- **Manufacturing**
  - Injection/Compression
  - Draping
  - Additive manufacturing

- **Performance**
  - NVH/Stiffness
  - Crash/Strength
  - Durability/Fatigue

- **Technology**
  - Linear/Nonlinear
  - Mean Field/Finite Element
  - Micro/Hybrid